DESCRIPTION

LASER PROCESSING APPARATUS

BACKGROUND OF THE INVENTION

5   The present invention generally relates to a laser processing apparatus for processing articles using a laser beam, and more particularly, to a laser processing technique applied to fabrication of high-precision components requiring a resolution of several microns to several hundred nanometers, as well as two-

10   dimensional or three-dimensional shape-processed devices (such as micro-electric-mechanical systems (MEMS) devices or diffractive optics) and components with a number of fine holes, such as photonic crystals, printed boards, or inkjet heads.

         Because a laser beam can converge accurately on a fine area

15   in short time, it is used in various types of processing, including direct material processing and indirect processing making use of chemical change, reformation or alteration of the material. Direct processing includes surface patterning, drilling, ablation, and cutting of metals or synthetic resins. Examples of

20   indirect processing include lithography and optical molding. Especially, in recent years and continuing, laser processing is often employed in superfine two-dimensional or three-dimensional shape processing to fabricate refractive and diffractive optical devices, master disks of optical disks, electric circuits, MEMS

25   devices, etc.

Conventionally, there are several methods for performing

shape processing using a laser beam, including:

(1) focusing the beam directly onto the object to be processed,

while moving the focal point or the object (relative to each

5   other); and

(2) guiding the beam through a mask to project the mask pattern

onto the surface to be processed.

The first method (1) is grouped into two categories depending

on which one of the object and the beam is moved, that is, moving

10   the object to be processed in a direction perpendicular to the

optical axis of the laser beams, or scanning the focal point using

a galvano scanner. The method using the galvano scanner generally

achieves faster and more precise processing; however, the

throughput falls when surface processing or pattern processing

15   over a wide area is performed.

The second method (2) allows collective processing of highly

precise patterns by scaling down the mask pattern and projecting

the downscaled pattern onto the surface to be processed. In

addition, three-dimensional processing is possible using a gray

20   scale mask. However, this method has the following problems:

(a) Since the light beam is blocked by a mask, light use

efficiency becomes very low depending on the pattern to be

projected; and

(b) Variation in light intensity guided to the mask leads to

unevenness of the resultant shape of the processed products.

To solve these technical problems, it is proposed to use a diffraction optical device or a hologram to perform collective shape processing at high light use efficiency. See, for example, JP 2002-66769A and JP 2001-272635A.

With this method, the light beam emitted from a coherent source is shaped using a device for modulating the phase and/or the amplitude of the light beam in order to acquire a desired beam shape on the processing surface.

By the way, it is required for a laser processing apparatus to perform positioning of the beam onto a processed site. Especially when performing high-resolution shape processing, positioning accuracy at or below one tenth of the resolution is required.

Conventionally, various methods for positioning the focusing point of the laser beam onto a desired position have been proposed, for example, by using a closed-loop type stage with position detecting equipment or a piezo element, or using a high angular-resolution galvano scanner. The above-described JP 2002-66769 discloses a combination of the hologram device and a galvano scanner to achieve precise shape processing over a wide area.

However, such a laser processing apparatuses is expensive, and in addition, it causers vibration due to mechanical movement of the movable part or element.

Another problem is that when the processing position moves in
the depth direction to process a three-dimensional shape or to
form a hole, the focal point has to be controlled along the
optical axis of the laser beam during the processing.

5   A conventional focal point control method employs an actuator
using a piezo element as the driving source in the focusing
optical system, or the stage on which a sample is fixed is driven.

With either method the apparatus become expensive because a
highly precise driving mechanism is required, and in spite of the

10   high-cost apparatus, the positioning accuracy is degraded due to
vibration due to acceleration or slowdown.

Other prior art publications in the laser processing field
are JP 2000-223766A and JP 2001-209003A. The former publication is
directed to a laser processing apparatus in which the phase of the

15   laser beam is modulated by modulation means structured by a liquid
crystal panel so as to change the focal position or the beam shape.
The latter publication is directed to a laser processing apparatus
having a laser source, an optical system for collimating the laser
beam emitted from the laser source into a parallel beam, and a

20   spot shape transforming device for guiding the parallel beam onto
the surface to be processed with a desired intensity distribution
profile. The spot shape transforming device has functions of a
lens and a spot shaper, and it controls the direction of the beam
and redistributes the beam intensity so as to achieve a prescribed

intensity distribution on the target surface. These two

publications simply disclose known laser beam control techniques

in the laser processing field, and further explanation is withheld.

5   SUMMARY OF THE INVENTION

        The present invention was conceived in view of the above-

described problems in the prior art, and an embodiment of the

present provides a laser processing apparatus that can achieve

high positioning accuracy and high light use efficiency without

10   using an expensive positioning mechanism, while preventing

degradation of positioning accuracy due to vibration of the

mechanically moving parts.

        In one aspect of the invention, a laser processing apparatus

includes:

15   (a) a laser source;

(b) a spatial phase modulator configured to modulate a phase of a

laser beam emitted from the laser source;

(c) a synthetic data generator configured to generate synthetic

data by combining hologram image data representing a pattern image

20   to be processed with position displacement hologram data for

shifting the pattern image to a prescribed position, said

synthetic data being input to the spatial phase modulator for the

phase modulation of the laser beams; and

(d) a focusing optical unit configured to guide the phase-

modulated laser beam onto a surface to be processed to reproduce

the pattern image on the processed surface.

By adding the position displacement hologram data to the

hologram image data representing a prescribed pattern image,

5   synthetic data containing position displacement information are

produced. By modulating the phase of the laser beams using the

synthetic hologram data, the pattern image is reproduced and

processed at a desired position on the processed surface, while

maintaining the light utilization efficiency high. The pattern

10   image reproducing function and the positioning function are

realized by a single spatial phase modulator.

BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the present invention will

15   become more apparent from the following detailed description when

read in conjunction with the accompanying drawings, in which:

FIG. 1 is a schematic diagram illustrating a laser processing

apparatus according to an embodiment of the present invention;

FIG. 2 illustrates an example of computer-synthesized

20   hologram data to be input to a spatial phase modulator;

FIG. 3 illustrates another example of computer-synthesized

hologram data to be input to the spatial phase modulator;

FIG. 4A through FIG. 4C illustrate examples of horizontal

position displacement hologram data to be added to the hologram

image data of the processed pattern to adjust the processing

position within a plane parallel to the processed surface;

FIG. 5 illustrates still another example of computer-

synthesized hologram data to be input to the spatial phase

5   modulator;

FIG. 6 is a schematic diagram illustrating a modification of

the laser processing apparatus according to an embodiment of the

invention;

FIG. 7 is a schematic diagram illustrating another

10   modification of the laser processing apparatus according to an

embodiment of the invention;

FIG. 8 is a schematic diagram illustrating still another

modification of the laser processing apparatus according to an

embodiment of the invention;

15   FIG. 9 is a schematic diagram illustrating yet another

modification of the laser processing apparatus according to an

embodiment of the invention;

FIG. 10 is a schematic diagram illustrating yet another

modification of the laser processing apparatus according to an

20   embodiment of the invention; and

FIG. 11A and FIG. 11B are diagrams for explaining step-and-

repeat processing, where FIG. 11A shows the first processing

result and FIG. 11B shows the second processing result.

PREFERRED EMBODIMENTS OF THE INVENTION

The preferred embodiments of the present invention are

described below with reference to the attached drawings.

(First example)

5   FIG. 1 is a schematic diagram of a laser processing apparatus

of the first example according to an embodiment of the invention,

and FIG. 2 illustrates an example of synthesis of a hologram image

to be processed.

The laser processing apparatus includes a laser source 11, a

10   spatial phase modulator 13, a focusing lens 14, a controller 16,

and a computer 17. The laser beam 12 emitted from the laser source

11 is subjected to phase modulation at the spatial phase modulator

13, and guided by the focusing lens 14 onto the object 15 to be

processed. The spatial phase modulator 13 is controlled by the

15   controller 16. The compter 17 generates and supplies input data to

the controller 16.

The laser source 11 is, for example, a second-harmonic 532 nm

YAG laser. The focal length "f" of the focusing lens 14 is 10 mm,

and the distance "d" from the spatial phase modulator 13 to the

20   focusing lens 14 is 10 mm.

The spatial phase modulator 13 produces a phase difference

making use of, for example, orientation of liquid crystal, an

electric-optical effect, or a magneto-optical effect. Using the

electro-optical effect or the magneto-optical effect is preferable

because of fast response speed. The spatial phase modulator 13 may

be of a reflective type or a transmission type. In this example, a

transmission phase modulator 13 making use of an electro-optical

effect is used; however, a reflective phase modulator may be used.

5   The spatial phase modulator 13 has 512×512 pixels at pixel pitch

of 30 μm and 256 gray scale levels in 2π phase modulation with

respect to the laser beam.

FIG. 2 illustrates an example of data to be input to the

spatial phase modulator 13. Image 21 defines a shape to be

10   processed on the object 15. Computer-generated hologram image data

22 are computed by the computer 17 so as to reproduce the image 21.

The computer-generated hologram image data 22 comprise 512×512

pixels defined by 256 gray scale levels, and the maximum of 2π

phase modulation can be given to the computer-generated hologram

15   image data.

To calculate the hologram, recursive Fourier transforms or

simulated annealing may be employed. Such algorithms are disclosed

in, for example, N, Yoshikawa and T. Yatagai, Appl. Opt. 33, 863-

867 (1994), and J. Fienup, Opt. Eng. 19, 297-305 (1980).

20   Recursive Fourier transforms can calculate a hologram of a

large number of pixels in a short time, as compared with simulated

annealing.

The hologram image data 22 representing a pattern to be

processed are combined with position displacement hologram data 23

to produce synthetic hologram data 24, which data are input to the

spatial phase modulator 13. In this context, "combining" the data

sets 22 and 23 is a process for adding the position displacement

hologram data 23 to the hologram image 22 to give a computed phase

5   modulation to each pixel. In this process, if the computed phase

modulation exceeds the maximum (or allowable) phase modulation 2π

at an arbitrary pixel, 2π is subtracted from the computed phase

modulation and the residual is used as the input data.

The position displacement hologram data 23 are data for

10   displacing the reproduced position of the hologram image, and they

are also computed using the above-described suitable algorithm.

(Example 2)

The position displacement hologram data 23 may be synthetic

data defined by a combination of horizontally adjusting hologram

15   data for controlling displacement in a direction parallel to the

processed surface and vertically adjusting hologram data for

controlling displacement in a direction perpendicular to the

processed surface. With this arrangement, the position

displacement hologram data set 23 is generated in a simpler manner.

20   Again, "combining" the horizontal hologram data and the vertical

hologram data is a process for adding these two data sets together,

and if the resultant phase modulation exceeds 2π, the residual

obtained by subtracting 2π from the added phase modulation is used

as the input data. If phase modulation is required only in a

direction perpendicular or parallel to the processed surface, the

required data set is solely added.

(Example 3)

FIG. 3 illustrates another example of synthetic hologram data

5   used in the laser processing apparatus according to an embodiment

of the invention, and FIG. 4A through FIG. 4C show examples of

position displacement hologram data 33 to be combined with the

computer-synthetic hologram image data.

The synthetic hologram data 34 produced in FIG. 3 are used in

10   a laser processing apparatus shown in FIG. 1 to adjust the laser

beam spot position only in a direction parallel to the processed

surface. Based on the image 31 representing a shape to be

processed, computer-synthesized hologram image data 32 are

calculated so as to reproduce the image 31 on the processed

15   surface. To shift the image reproducing position along the

processed surface, horizontal position displacement hologram data

set 33 having a sawtooth phase distribution profile in this

example is added to the hologram image data 32. The resultant

synthetic data 34 are input to the spatial phase modulator 13.

20   If the hologram image data 32 are solely input to the spatial

phase modulator, without adding the position displacement hologram

data 33, then a pattern image 35 is reproduced at a reference

position on the processed surface. By adding the position

displacement data set 33, the position for reproducing the pattern

image is displaced and a reproduced image 36 is obtained. For the

purpose of clarifying the position displacement, vertical and

horizontal reference lines are depicted in the reproduced images

35 and 36.

5   For position displacement hologram data set 33, a suitable

phase distribution profile is determined, such as a sawtooth data

profile with asymmetric slopes illustrated in FIG. 4A. By

combining the sawtooth data set with the computer-generated

hologram image data 32 and by inputting the combined data (or the

10   synthetic data) to the spatial phase modulator 13, the laser beam

is tilted by angles θx and θy in the x and y directions,

respectively, and the image reproducing spot is displaced along

the processed surface corresponding to the tilting angles θx and

θy. The tilting angles θx and θy are several milliradians, and

15   paraxial approximation can be applied.

Detailed explanation is made of determination of the sawtooth

data below. When the laser beam is tilted by the spatial phase

modulator 13 by angles θx and θy in the x and y directions,

displacements Δx and Δy in the x and y directions on the

20   processed surface are expressed by

$$\Delta x = \tan \theta x * (2-f/d), \text{ and}$$

$$\Delta y = \tan \theta y * (2-f/d),$$

where f denotes the focal length of the focusing lens, and d

denotes the distance from the spatial phase modulator 13 and the

-13-

focusing lens 14 (see FIG. 1).

The phase modulation $\phi(x, y)$ at coordinates x and y in the spatial phase modulator is expressed by

$$\phi(x,y)= 2\pi\ (x\frac{a_x}{\lambda}\tan\theta_x+y\frac{a_y}{\lambda}\tan\theta_y)-m\cdot 2\pi$$
$$= 2\pi\ (x\frac{a_x}{\lambda}\frac{\Delta x}{(2-f/d)}+y\frac{a_y}{\lambda}\frac{\Delta y}{(2-f/d)})-m\cdot 2\pi$$

5   where a_x and a_y are pixel pitches of the spatial phase modulator in the x and y directions, respectively, and "m" is an integer multiplied so as to maintain $\phi(x, y)$ within the range from 0 to 2 π.

The positioning accuracy using the position displacement data
10   (sawtooth data, for example) is explained below. The minimum inclination of wavefront given by the sawtooth data is expressed by

$$\lambda\times(8/M)/Na$$

where λ is the wavelength of the laser beam, M is the modulation
15   level, N is the number of pixels, and a is the pixel pitch. In this example, there are eight modulation levels to define minimum inclination of wavefront. Setting eight modulation levels is supposed to be sufficient because the theoretical diffraction efficiency of 98 % can be achieved.

20   Under these conditions, the minimum inclination of wavefront is about 1.9 microradians, which value is regarded as the minimum resolution. As compared with typical positioning accuracy of a

-14-

galvano scanner ranging from 5 microradians to 10 microradians,

higher positioning accuracy at higher resolution can be achieve in

this embodiment without using mechanical components. The

corresponding laser beam positioning accuracy on the processed

5   surface is about 20 nm. This accuracy is defined by the

performance of the spatial phase modulator 13, and if the number

of pixels or the number of modulation levels is increased, still

more accurate positioning can be performed.

The horizontal position displacement data set 32 is not

10   limited to the sawtooth data shown in FIG. 4A, and other suitable

phase distribution profiles, such as a stepwise or quantized data

profile shown in FIG. 4B, or a simply sloped data profile shown in

FIG. 4C may be employed. In addition, the slope of the data

profile is not limited to a straight line, but a slightly curved

15   profile is also acceptable.

(Example 4)

FIG. 5 is a schematic diagram illustrating still another

example of synthetic hologram data used in a laser processing

apparatus. In this example, synthetic hologram data 44 contain not

20   only horizontal position displacement information in a direction

parallel to the processed surface, but also vertical position

displacement information in a direction perpendicular to the

processed surface. Such synthetic hologram data can be used in the

laser processing apparatus shown in FIG. 1.

In addition to the horizontal position displacement data (sawtooth data in this example) 43, vertical position displacement data 45 with a phase distribution similar to a Fresnel zone plate are added to the computer generated hologram image data. With this

5   arrangement, synthetic hologram data set 46 horizontally and vertically modulated is input to the spatial phase modulator 13.

To be more precise, computer-generated hologram image data 42 are calculated based on the pattern image 41 so as to reproduce the pattern image on the processed surface. The sawtooth data 43,

10   which are the horizontal position displacement data used to displace the beam spot within a plane of the processed surface, are added to the computer-generated hologram image data 42, and horizontally modulated synthetic data 44 are produced. Then, the Fresnel zone plate data 45, which are vertical position

15   displacement data used to displace the beam spot in a direction perpendicular to the processed surface, are further added to the horizontally modulated synthetic data 44. Consequently, horizontally and vertically modulated synthetic data set 46 is obtained. If the final modulation amount exceeds 2π, then an

20   integer multiple of 2π is subtracted from the modulated data set 46 to produce input data to the spatial phase modulator 13.

The vertical position displacement data 45 with the Fresnel zone plate like phase distribution have a function similar to a Fresnel lens, and they can add a desired radius R of curvature to

the wavefront of the laser beam. The Fresnel zone plate data 44 are not necessarily perfectly continuous data, but may be quantized slightly modified so as to reduce the data amount.

(Example 5)

5   When using the horizontally and vertically modulated hologram data (synthetic hologram data) 46 shown in FIG. 5, the laser processing apparatus is configured to maintain the image size reproduced on the processed surface constant regardless of the focal length of the added Fresnel zone plate data 45. For this

10   reason, the distance "d" from the spatial phase modulator 13 to the focusing lens 14 is set equal to the focal length "f" of the focusing lens 14.

In this example, a single lens 14 is used as the focusing lens system; however, a combination of multiple lenses may be

15   employed as the focusing lens system. In that case, the lens processing apparatus is configured such that the composite focal length "f" of the focusing lens system becomes equal to the distance from the spatial phase modulator 13 to the combined principal plane of the focusing lens system.

20   If a lens with focal length f1 and a lens with focal length f2 are positioned at distance "d", the composite focal length f' of the combined lens system is given by

$$\frac{1}{f'} = \frac{1}{f1} + \frac{1}{f2} - \frac{d}{f1 f2}$$

Accordingly, if d=f2, then the composite focal length f' becomes

f2 (a constant value) regardless of the value of f1.

If the focal length of the Fresnel zone plate data 45 to be

input to the spatial phase modulator 13 is f1, and if the focal

5   length of the focusing lens system is f2, then, the composite

focal length becomes constant at f2 by setting the distance from

the spatial phase modulator 13 to the focusing lens system to f2.

Accordingly, the image size of the pattern reproduced on the

processed surface becomes constant regardless of the focal length

10   of the Fresnel zone plate data 45.

In this condition, the displacement Δz of the focal position

is expressed by

$$\Delta z = f^2/R$$

where f is a focal length of the focusing lens system, and R is a

15   radius of curvature given to the wavefront of the laser beam by

the Fresnel zone plate data 45.

On the other hand, the phase modulation $\phi(x, y)$ at

coordinates x and y of the spatial phase modulator 13 is expressed

as

$$\phi(x,y) = \left(R - \sqrt{R^2 - (a_x^2 x^2 + a_y^2 y^2)} \right) - m \cdot 2\pi$$
$$= \left(f^2/\Delta z - \sqrt{f^2/\Delta z - (a_x^2 x^2 + a_y^2 y^2)} \right) - m \cdot 2\pi$$

20   where a_x and a_y are pixel pitches of the spatial phase modulator in

the x and y directions, respectively, and m is an integer

multiplied so as to maintain $\phi(x, y)$ within the range from 0 to 2

π.

(Example 6)

FIG. 6 is a schematic diagram illustrating a modification of

the laser processing apparatus according to an embodiment of the

5   invention. The laser processing apparatus is furnished with a

wavefront measuring device 52 for the purpose of preventing

adverse effect on the processing accuracy due to distortion of the

wavefront of the laser beam. A beam sampler 51 is inserted between

the laser source 11 and the spatial phase modulator 13 to guide a

10   portion of the laser beam toward the wavefront measuring device 52.

The same elements as those shown in FIG. 1 are denoted by the same

numerical symbols and explanation for them is omitted.

A portion of the laser beam emitted from the laser source 11

is extracted by the beam sampler 51, and is incident on the

15   wavefront measuring device 52. The wavefront measuring device 52

is, for example, of a Shack Hartmann type using a microlens array,

or of a type splitting the beams to cause interference for

measurement of the wavefront.

The signal output from the wavefront measuring device 52 is

20   input to the computer 17. The computer supplies data for

correcting the distortion of the wavefront to the spatial phase

modulator 13 to correct the distortion of the wavefront of the

laser beam.

(Example 7)

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FIG. 7 is a schematic diagram illustrating another

modification of the laser processing apparatus according to an

embodiment of the invention. In this modification, the laser

processing apparatus is furnished with an intensity and/or

5   irradiation time adjusting structure.

The laser processing apparatus shown in this example is

configured to accurately control processing depth and three-

dimensional processing shapes by regulating the intensity and the

irradiation time of the laser beam. To be more precise, a half

10   (1/2) wave plate 61, a Glan-Thompson prism 62, and a shutter 63

are inserted between the laser source 11 and the spatial phase

modulator 13. The elements the same as those shown in FIG. 1 and

FIG. 6 are denoted by the same numerical symbols, and explanation

for them is omitted.

15   The laser beam emitted from the laser source 11 passes

through the half wave plate 61, the Glan-Thompson prism 62, and

the shutter 63, and is incident on the spatial phase modulator 13.

Since in general the laser beam emitted from the laser source 11

is a linearly polarized beam, the intensity of the laser beam

20   passing through the Glan-Thompson prism 62 can be regulated by

adjusting the angle of the half wave plate 61. When the linear

polarization of the laser beams is not so strong, two Gran-

Thompson prisms may be arranged. In this case, the laser beam

intensity can be adjusted by rotating the direction of one of the

-20-

Gran-Thompson prisms.

The laser beam irradiation time (or the number of laser

pulses) is adjusted by the shutter 63. The shutter 63 may be

mechanically operated, or alternatively, it may employ an acoustic

5   optical device or an electrooptical device. In the example shown

in FIG. 7, both the intensity modulating device and the

irradiation time (or laser pulse number) control device are

provided; however, it is possible to use only one of them in the

laser processing apparatus.

10   (Example 8)

FIG. 8 is still another modification of the laser processing

apparatus according to an embodiment of the invention. In this

modification, the laser processing apparatus is furnished with an

end-measuring device 71 to measure the position of the object to

15   be processed, in addition to the beam intensity/irradiation time

adjusting mechanism shown in FIG. 7.

The laser processing apparatus shown in FIG. 8 is configured

to perform precise processing at a desired position along the

surface of the object by measuring the position of the object

20   being processed from two directions. The components the same as

those shown in FIG. 1, FIG. 6 and FIG. 7 are denoted by the same

numerical symbols and explanation for them is omitted.

A pair of end-measuring laser devices 71 are attached to, for

example, the stage (not shown) for holding the object 15 in two

directions with respect to the object 15, within a plane

perpendicular to the laser beam, to measure the position of the

object 15. The signals from the end-measuring device 71 are fed

back to the computer 17.

5   (Example 9)

FIG. 9 is a schematic diagram illustrating still another

modification of the laser processing apparatus. The laser

processing apparatus of this modification is furnished with an

observation mechanism.

10   The laser processing apparatus shown in FIG. 9 is configured

to achieve higher positioning accuracy by monitoring the position

to be processed. A dichroic mirror 81 is inserted between the

spatial phase modulator 13 and the focusing lens 14. In addition,

a microscope lens barrel 82, a CCD camera 83, and a lamp 84 are

15   provided. The components the same those shown in the previous

examples are denoted by the same numerical symbols and explanation

for them is omitted.

Because the dichroic mirror 81 for reflecting only the laser

beam is placed before the focusing lens 14, the processing

20   position can be observed by the microscope lens barrel 82 and the

CCD camera 83 through the diachronic mirror 81 and the focusing

lens 14. It is desired that the processing position is illuminated

by the lamp 84. The image captured by the CCD camera 83 is input

to the computer 17. The computer 17 reads features on the

-22-

processed surface to specify the irradiating position of the laser beam. This information is reflected in generation of position displacement data.

The features on the processed surface include alignment marks
5   provided in advance and edges of the object 15. If the laser processing is applied to direct shaping, the processed shape achieved so far can also be used as the feature on the processed surface.

During the observation, the laser beam may be switched off,
10   or alternatively, the intensity may be reduced below the processing threshold. In the latter case, the laser beam spot position can also be observed by the CCD camera 83, and the positional relation between the laser spot and the alignment mark is fed back to the computer 17 so as to achieve further precise
15   positioning.

(Example 10)

FIG. 10 is a schematic diagram illustrating yet another modification of the laser processing apparatus according to an embodiment of the invention. The laser processing apparatus
20   further includes a stage 90 for moving the object 15, in addition to the structure shown in FIG. 9. FIG. 11A and FIG. 11B are schematic diagrams for explaining step-and-repeat processing using the laser processing apparatus shown in FIG. 10.

This laser processing apparatus is configured to achieve fine

processing over a wide area, while maintaining the positioning

accuracy sufficiently high. The components the same as those shown

in the previous examples are denoted by the same numerical symbols

and explanation for them is omitted.

5   The object to be processed is fixed on a biaxial stage 90

movable in a plane perpendicular to the irradiation of the laser

beams. The biaxial stage 90 is an inexpensive automatic stage with

repeat-positioning accuracy at or above several hundred microns.

The output from the CCD camera 83 is supplied to the computer 17,

10 and the information about the processing position is reflected in

the hologram data input to the spatial phase modulator 13.

When performing step-and-repeat processing, a pattern 91 is

formed at the first processing, as illustrated in FIG. 11A. During

the first processing, alignment marks 92 are also formed. The

15 alignment marks 92 are used for alignment of the second and the

subsequent processing. Then, the stage 90 is driven and alignment

is performed for the second processing, using the method described

in the previous example in conjunction with FIG. 9. Then, the

second processing is performed to form pattern 93, as illustrated

20 in FIG. 11B. Again, alignment marks are formed together with the

pattern 93.

(Example 11)

Although not illustrated in figures, explanation is made of

several more modifications. In a further modification, measuring

equipment for measuring the distance between the focusing lens 14

and the object 15 may be further provided in the laser processing

apparatus (any one of the apparatuses shown in FIG. 1, and FIG. 6

through FIG. 10) to precisely control the hologram image

5   reproducing position along the optical axis of the laser beam. The

measuring equipment makes use of astigmatism, triangulation, or

other suitable measuring methods. The signals from the measuring

equipment are fed back to the computer 17 to generate hologram

data containing displacement information in a direction

10   perpendicular to the processed surface.

(Example 12)

In another modification, the laser processing apparatus may

be configured so as to greatly shift the focal position by

providing a stage for holding the object 15 and the stage being

15   driven along the optical axis of the laser beam to the structure

shown in FIG. 1, and FIG. 6 through FIG. 10).

By driving the stage along the optical axis of the laser

beams, the distance between the focusing lens 14 and the object 15

can be changed greatly to shift the focal position perpendicular

20   to the processed surface. This arrangement is suitable for

processing an object with bumps or steps or forming grooves or

holes.

(Example 13)

The laser processing apparatus may be configured to reduce

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influence of thermal propagation of the laser beam. In the laser

processing apparatuses shown in FIG. 1 and FIG. 6 though FIG. 10,

the laser source 11 may be replaced with a ultra-short pulse laser

with a pulse width of several picoseconds or less. An example of

5   the ultra-short pulse laser is a titanium sapphire laser with a

pulse width of 100 femtoseconds.

In direct processing, the surface shape of the object being

processed is directly changed by heat of the laser beam. The

energy of the laser beam propagates as heat to the irradiated

10   position, and the irradiated portion is vaporized or liquefied

causing the shape to be changed. During the irradiation, the

influence of heat propagation extends to the surrounding of the

irradiated position, which makes it difficult to perform precise

patterning. Especially in fine processing, the influence of heat

15   propagation cannot be neglected.

Using an ultra-short pulse laser with a pulse width at or

below several picoseconds, mutual interaction between the laser

beam and the object being processed is very short, and influence

of heat propagation can be prevented.

20   Because high energy is instantaneously generated by an ultra-

short pulse laser, energy efficiency is superior and materials

hard to process, such as diamond, glass, or oxides, can be

directly etched.

In addition, an ultra-short pulse laser has a high peak level,

and laser processing making use of two-photon absorption can be performed. This means that laser processing is carried out inside an object transparent with respect to the laser beam. Since the laser processing apparatus of the above-described examples is

5   capable of three-dimensional positioning, laser processing can be carried out at a desired position inside the transparent object at high positioning accuracy.

As has been described above, any one of the horizontal hologram data set representing displacement in a direction

10   parallel to the processed surface, the vertical hologram data set representing displacement in a direction perpendicular to the processed surface, and the combination of the horizontal and vertical hologram data sets can be used as the position displacement data.

15   Since the horizontal hologram data and the vertical hologram data are calculated separately and combined if necessary to generate the position displacement data, calculation time for producing the position displacement data is reduced and the processing rate can be improved.

20   By employing a sawtooth phase distribution for the horizontal hologram data set, the displacement hologram data representing desired displacement in a direction parallel to the processed surface can be produced in a simple manner. Based on the displacements Δx and Δy of the current laser beam spot from the

prescribed position, the sawtooth profile can be automatically determined by simple calculation.

When processing a complicated pattern, the pattern may be divided into simple sub-patterns. In this case, the laser

5   processing is repeatedly performed for each of the divided sub-patterns, while changing the hologram image data and the sawtooth displacement data. Although computational error becomes inevitably large in the calculation of a hologram image of a complicated pattern, reproduction error due to computation of the hologram

10   image can be reduced by dividing the pattern into simple sub-patterns.

Similarly, the vertical hologram data set having a phase distribution profile similar to a Fresnel zone plate can also be calculated in a simple manner. Using the Fresnel zone plate

15   hologram data, the laser irradiating position can be adjusted in a direction perpendicular to the processed plane (along the optical axis of the laser beam).

By setting the distance "d" from the spatial phase modulator to the focusing optical unit equal to the focal length "f" of the

20   focusing optical unit, the size of the reproduced hologram image can be maintained constant regardless of the focal length of the position displacement data with the Fresnel zone plate phase distribution. When reproducing the hologram image on the processed surface using the Fresnel zone plate position displacement data,

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the size of the reproduced hologram image generally changes

according to the focal length of the added Fresnel zone plate data

because the size of reproduced pattern image is determined by the

focal length of the Fresnel zone plate data, the focal length of

5   the focusing lens, and the positional relation between the spatial

phase modulator and the focusing lens. The above-described

arrangement overcomes this problem.

By providing a wavefront measuring unit to measure a

wavefront of the beam, and by feeding the measurement result to

10   the computer, information about correcting the distortion of the

wavefront can be reflected in the synthetic hologram data to be

input to the spatial phase modulator. Consequently, adverse

influence due to wavefront distortion can be prevented.

By further providing at least one of the irradiation time

15   adjusting unit configured to regulate irradiation time of the

laser beam and the beam intensity adjusting unit configured to

regulate intensity of the laser beam, the optimum intensity and/or

irradiation time can be set. Since the processing depth and shape

depend on the laser beam intensity and irradiation time (or the

20   number of pulses), using the optimum intensity and irradiation

time leads to high processing accuracy in the shape of the pattern.

If hologram images are generated by dividing a complicated pattern

into several sub-patterns, the laser irradiation time may be

changed for each of the sub-patterns to achieve accurate

reproduction of a three-dimensional shape.

When the laser processing apparatus is furnished with a horizontal-direction position detector for detecting a horizontal position in a plane parallel to the processed surface, horizontal

5   hologram data used to displace the pattern in a direction parallel to the processed surface can be generated accurately based on the detected position. Consequently, horizontal hologram data with, for example, an appropriate sawtooth phase distribution profile can be automatically determined.

10   By configuring the horizontal-direction position detector to detect a reference pattern formed on the processed surface, the target position to be processed can be fed back to the computer to perform accurate positioning. When direct shape-processing is performed, the surface observation result can be supplied to the

15   computer during the processing, and the laser irradiating position and intensity can be regulated in real time.

When a first driving unit for moving the light spot of the laser beam relative to the processed surface in a direction parallel to the processed surface is used to perform so-called

20   step-and-repeat processing, accurate processing can be performed over a wide area. In this case, rough adjustment is carried out by the first driving unit, and fine adjustment is implemented by the synthetic hologram data input to the spatial phase modulator. Accordingly, the first driving unit may be an inexpensive one with

positioning accuracy at or above 10 μm.

When the laser processing apparatus is furnished with a
vertical-direction position detector for detecting a relative
positional relation between the focusing lens and the processed
5   surface, vertical hologram data used to displace the pattern in a
direction perpendicular to the processed surface can be generated
accurately based on the positional relation.

To reproduce a hologram image at a correct position in a
direction perpendicular to the processed surface, the distance
10   between the focusing lens and the processed surface is important.
In step-and-repeat processing, the distance from the focusing lens
to the processed surface may vary due to unevenness of the surface.
Therefore, by supplying the measured distance to the computer, the
hologram image reproducing position can be precisely adjusted
15   along the optical axis of the laser beam.

By providing a second driving unit for moving the light spot
of the laser beam relative to the processed surface in a direction
perpendicular to the processed surface, a three-dimensional shape
with conspicuous steps or deep grooves can be processed. With the
20   synthetic hologram data containing vertical displacement
information, the focal position can be adjusted up to several tens
of microns in a direction perpendicular to the processed surface.
To reproduce a three-dimensional pattern with a step or a groove
exceeding this level, the distance between the focusing lens and

the processed surface can be changed greatly by the second driving

unit.

By using an ultra-short pulse laser as the laser source,

adverse influence due to heat propagation can be reduced because

5   the interaction time between the laser beam and the processed

surface is very short. Consequently, a precise outline of the

pattern can be reproduced, preventing the influence of heat

propagation from expanding to the surrounding area. In addition,

with instantaneously generated high energy, direct processing can

10   be performed on a material hard to process.